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Requirement based Future Product Cost Estimation using Lifecycle Assessment Data

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Abstract

A key advantage of Product Lifecycle Management implementation is the use of data, coming from all phases of a product, for the optimisation of future goods. The aim is not only to create more robust and efficient products but also to decrease engineering efforts including revisions. In order to determine the prospective economic efficiency and be able to estimate its influence on the product's lifecycle prior to the development of a new design, it is essential not only to anticipate revenues but to have liable information about expected costs. With most approaches, focus lies on the production expenses as they cause the significant share of total product costs. Engineering and development expenditures are in most cases not reliably to identify at project start, since too many factors of influence impede realistic predictions. Given methods typically premise the availability of accurate values as input parameters: extrapolation techniques often base upon BOM positions and other methods consider specific attributes of the future product, which are not definable at this point of time. To overcome this drawback, a new approach has been developed. This methodology is based on requirements and known technical parameters from which characteristic factors are derived that are merged to a dimensionless number, likewise the concept of similarity indicators. Assuming that products with a similar dimensionless number also cause similar development costs, databases from previous products can be set up and the factors assessed, allowing for a direct development cost comparison with future products. The approach has been evaluated in the civil aircraft industry under consideration of the main concept requirements, the so called Top Level Aircraft Requirements. A retrospective analysis of existing aircraft concerning development costs and their requirements provided the needed input to calculate the dimensionless number and to create reference values. Conventional as well as innovative aircraft have been researched to also allow an estimation of expenditures for bringing new technologies to market. Approach and evaluation are presented in detail and information about the software prototype that was integrated into a lifecycle assessment platform is given. It was developed in the 4-year term of a project funded by the German Universities Excellence Initiative.

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1. Introduction

To estimate the economic feasibility of a new product development project, it is vital to obtain knowledge about both the expected revenues and occurring costs.

However, in most cases, solely estimating the effort for the engineering design prior to or within the early phases of the product development is not possible in a reliable way. Influencing parameters are regularly not quantifiable and their number is often too high, which renders forecasts imprecise and thus leads to unreal cost predictions.

Often, forecasts are also limited particularly to a prediction of the expected manufacturing and assembly costs disregarding the expenditures for engineering design departments and the actual product development process. Existing methods like the feature based cost information system FEKIS [1] or the extended cost information system XKIS [2] allow for estimation – partly already synchronous to the product development phase – of the efforts caused by engineering design departments. Even though those efforts typically exceed the development costs [3], enterprises are increasingly forced to significantly reduce the expenditures

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for the execution of development projects besides reducing the production costs itself [4].

In many cases, existing methods used to estimate the prospective effort for the development are designed to predict comparably accurate data and thus require precise input values respectively. Some are based on extrapolation approaches which take into account the number of positions in the bill of materials (BOM) to predict the expected effort. Others require the precise knowledge of specific parameters of the entirely designed product, like masses of single parts. They provide equations that try to represent the mathematic correlation between those parameters and the development costs. However, in early phases of development projects, neither all BOM positions are available nor all parts are given their final shape, volume and mass. Hence, the required input parameters are not defined with the necessary granularity.

However, to still be able to estimate forecasts of the expected effort for the development phase in this stadium, despite the prevailing diffused level of concretion, a method is required that bases on few, already known technical parameters, so called design parameters, which are derived from basic requirements and in addition are defined a priori.

2. State of the art

Cost estimation methods for the effort of product development projects to be applied in early stages are barely described within conventional systematic engineering design methodologies. Typical approaches are based on estimations using experiences from predecessor projects related to similar products. For example, one common method is to estimate the amount of required technical drawings and specification documents and convey these numbers into the necessary area of paper, which can be expressed as multiples of a standard document square meter. By correlating this number with standardised working hours or more precise company internal empirical values for the needed time to create one document square meter, estimating the actual effort is enabled. However, this approach requires precise knowledge about the product structure and moreover the number and especially the kind of the components currently under development. [5] For this reason, the method is not qualified as a prediction method for the expected effort determined prior to or during the engineering design phase.

Similar at the core are approaches that take into account the expected number of BOM positions and correlate them with other, typically company internal performance indicators like the required working hours per position. Analogous with approaches of this type is the required precise knowledge about the bill of materials of the product under development to estimate precise values for the effort.

However, since several decades the software industry uses estimation methods that aim at predicting the effort of the development phase itself. Software products typically invoke design and development costs whereas the production from a conventional point of view – if any – is restricted to manufacturing the volume and packaging. The Constructive Cost Model (COCOMO) has been introduced in 1981 by Barry Boehm [6]. Since then it has been continuously extended but at its core is still based on the estimation of the effort that is correlated to the expected size of the software. Thereby, the size is considered as the amount of source code evaluated in so called source lines of code (SLOC). In addition to this measure, further seventeen parameters, which have to be estimated before the method is executed, are introduced. Amongst others, the parameters comprise key figures for the complexity of the design, the similarity with already executed development projects, the intended reliability of the future software product, and the ability for collaboration of the engineering team. [7]

A prototypical adaption towards the needs of conventional product development in the sector of mechanical engineering design has already been conducted [8]. To achieve this, the seventeen parameters of the COCOMO-II model have been adjusted to the special necessities of the discipline and consolidated into a total of seven parameters. While some of the seventeen initial parameters do not have a direct equivalent in engineering design, others are immediately applicable. For example, the grade of innovation as a result of the expected novelty of a product is comparatively easy to measure [9] and thus utilisable for the intended effort estimation. In addition to that, parameters like the similarity with previously conducted projects and the qualification of the staff can be implemented. The latter has significant influence especially with regard to the distribution of the team over several sites. Although many of the required parameters are known a priori or can be determined independently from the product under development, the actual size of the product (being the equivalent to the expected SLOCs, for example the number of BOM positions) is indispensable. Thus, this method is also not qualified as a tool that takes technical parameters into account to forecast the expected development effort before the development project has started in an adequate way.

Specialised for civil and military aircraft development and design several methods have been set up that intend to estimate the lifecycle costs (LCC) of an aircraft. In particular, development costs are addressed. Raymer, for example, presents an equation, to determine the required engineering hours that are needed for the design of a specific type of aircraft. The equation is based on cost estimation relationships (CER) and includes parameters like the mass (operating empty weight, OEW), the maximum speed and the size of the aircraft. With the help of company specific coefficients, the estimated engineering hours can be transformed into the expected costs [10]. However, this equation is only valid for aircraft whose design incorporates aluminium as the main material for vessel as well as wings. This makes its application unmanageable for modern era aircraft that utilise increasing amounts of new materials like composites and fibre reinforced plastics or metals (e.g. glare). Moreover, a generalisation of the approach to cover other fields besides the aerospace industry is not possible without significantly revising the equations. In addition to this approach, Raymer presents a further method that tries to anticipate the development costs as a fixed portion of the production costs [10]. However, this method requires the precise information about all production efforts. In general, those estimations are only available towards the end or even only after the development project. This fact impedes the application of the method in early phases of the development project.

An approach that is likewise specialised for aircraft design is presented by Roskam. He predicts development costs in relation to the masses of few key components. It requires the empty weight of the overall aircraft as well as the masses of landing gear, braking systems, engines and coolants in addition to all parts made from rubber as well as the masses of batteries, avionics, fire extinguishing systems, air conditioning systems and the mass of the auxiliary power unit (APU) before any forecast can be conducted. [11]

These precise values typically are not available for a new product at the beginning of the development project. A further disadvantage regarding the adoption of the method is the aged data originating from the early seventies of the 20th century upon which all mathematical relations are constructed. A simple refreshment of the database does not lead to satisfying results as fundamental technological innovations are not considered in the underlying equations. Moreover, an extension of the model covering other industrial sectors seems to be challenging because of the specific inclusion of aircraft related physical components.

As not every development project can be considered as new product development, forecasting methods that address the latter cannot be applied for follow-up designs. Roskam suggests a so called difficulty factor as a means for the complexity of the development, which however, is to be multiplied with the estimated costs on a basis of personal discretion, to achieve more realistic results. [11]

Concluding, existing methods enable engineering departments to estimate the effort of the development projects expressed by the engineering hours needed respectively to estimate the costs directly. However, every method requires precise values as input that typically are not available prior to or during the early design phase. In addition, their knowledge exceeds the technical parameters that are available. Consequently, their application is limited to later phases of development projects when many parts are already designed with their definite shapes and masses.

3. Methodology for estimating the effort

To overcome this unsatisfactory state, a methodology aiming at the prediction of the development effort must be elaborated. The key requirement for the methodology is, to be operationally based on technical parameters and to forecast the expected effort of the engineering design project upon them prior to or during its early phase.

3.1. Conception and structure of the methodology

The methodology is comprised of two methods. The first aims at setting up and qualifying the model whose purpose is to supply the lifecycle data that is needed by the second method. The latter is executed when actually performing the forecasting of the development effort for a specific product. Thus, the second method is the actual method an intended operator will utilise. However, it requires a functional data model, which in return requires the successful execution of the first method at least one time, before a first prediction can be conducted. Fig. 1 gives an overview of the structure of the methodology with its two basic methods as well as the general procedure for the estimation of the effort in the course of a product development process.

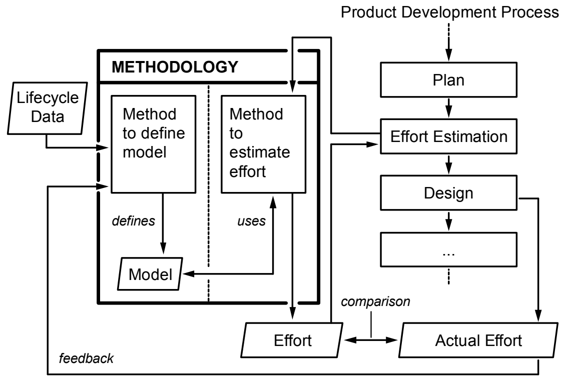

Fig. 1. Structure of the methodology and procedure for estimating the effort

The main hypothesis used to establish the methodology relies on the postulation that products can be described by a set of physical parameters. Overall or maximum mass respectively volume may serve as an example. In addition to that, the hypothesis assumes that these parameters can be used to deduce correlations with economically determining factors, like the development effort. It is assumed that products with similar factors cause similar effort. In general, three types of correlations can be identified: effects of scale, models based on statistics and equation-based, mathematical descriptions [12]. The latter will be researched for application within the presented methodology. Moreover, a second hypothesis is established which addresses the fact that development effort is closely related to the year in which the corresponding project takes place. It seems to be legitimate to assume that – with regard to progressing technological change – the engineering of a specific product at a given time has induced a significantly higher effort concerning the development project, than the same engineering of the same product conducted decades later (experience curve effect).

3.2. Method for the modelling of lifecycle data

Before the method for the estimation of the effort can be applied, the underlying model has to be set up. A consecutive qualification step ensures the proper establishment of the mathematical relations between technological parameters and desired economic key figures. The required steps are given in Fig. 2.

The first step is the estimation of a suitable set of technical parameters. Here, suitable refers to utilising those parameters that are defining the later product in an unambiguous way and at the same time have a significant influence on the development effort. Hence, the overall maximum mass is a more suitable parameter as the colour for example. The latter typically has no influence at all or just a considerably low influence on product development. In addition to that, it was discovered as helpful to form combinations of different single technical parameters in order to obtain a more qualified indicator for the overall effort. For instance, the required length of the landing field itself is a good indicator for the effort as aircraft, that only need a short landing field, are in general more difficult to design. However, if the maximum landing weight is put into relation with the landing field length, the indicating effect is emphasized as it is more difficult to design an aircraft that is both heavy and requires only a short landing field. In general, any technical parameter and any combination formed by them, is suited for the modelling process. Nevertheless, the quality and the performance of the model increase significantly the more informative the parameters are.

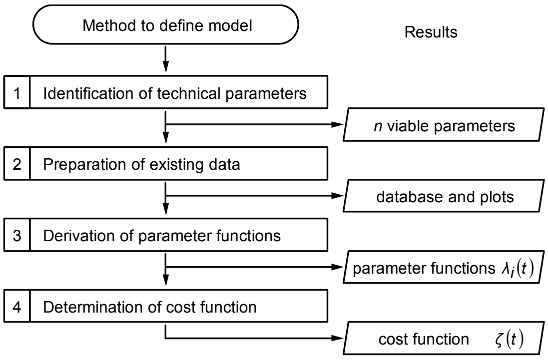

Fig. 2. Steps and results of the method for qualifying the model

The method presented here relies heavily on the analysis of already existing data ranging from both the lifecycles of the product and its predecessors as well as from those data taken from competitors offering similar products. This implies that before training and eventually using the model, enough data has to be generated or researched and subsequently prepared to qualify the model. Hence, in a second step, the model has to be supplied with solid values of already successfully conducted development projects. For every parameter that has been selected in the first step, values have to be present and correlated with the year in which the actual product was designed.

The third step comprises the constitution of a so called parameter function, referred to as $\lambda_i(t)$. To derive this function, all couples of parameter values and the corresponding year are entered into the parameter value plot. Exemplarily, such a diagram is given in Fig. 3. Depending on the type of product and the industrial sector the maximums respectively minimums (depending on the desired optimisation direction, e.g. noise values) of a defined time period are investigated. It has to be taken into consideration, that the length of the period has to be chosen individually and its optimal size depends on the duration a development process typically features in the respective industrial sector. In the depicted plot in Fig. 3, a higher parameter value is related to a higher development effort. In that case, the maximums of the particular periods are calculated. Based upon those values a non-linear smoothing function, the parameter function λ, is derived. If sufficient and moreover all representative development projects are plotted in the diagram, the parameter function resembles the average limit of the technological advancement of the assigned parameter in the specific year. Concluding, no other or only few development projects exist, that surpass this limit significantly. This step has to be repeated for every parameter chosen in the first step.

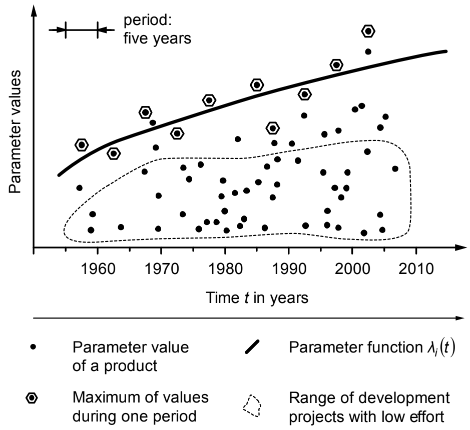

Fig. 3. Illustration of the parameter value function in the parameter value plot

The fourth step is conducted in order to obtain a function representing the development costs. Based upon the same data and similar to setting up the parameter value functions, the cost function is derived by plotting all costs in the respective plot. The maximums of the chosen period are calculated and a linear smoothing curve is estimated through these maximums. The cost function is referred to as ζ. To ensure comparability of the different results, only inflation-adjusted values should be taken into account.

The qualification phase of the model is finalised with having obtained both parameter value and cost functions with the help of the described parameter value and cost plots.

3.3. Method for the estimation of the development effort

Having qualified the model based upon lifecycle data of technical parameters as well as correlated costs, the estimation of the development effort for the product currently under observation can be commenced with. Fig. 4 shows the necessary steps of the approach including required inputs and results from each of the single steps.

At first, the technical parameters for the new product development have to be estimated. They are considered as the basic requirements typically being fixed before the actual design work begins and thus serve as the main input to the method presented here. In addition, the year in which the development takes place is required as the mathematical relations that the model is based on use existing lifecycle data to which the new parameters have to be put into context.

The next step addresses the forming of key figures from the parameters. They are used to search for principle similarities of the current development with existing data points. To achieve that, the ratio (key figure) ξ_i of the technical parameter Λ_i for the development project whose effort is to be estimated and the value of the corresponding parameter value function λ_i at the given time are calculated.

This key figure is a measure for the similarity of each parameter at any specified time *t* with a theoretical product that can be located precisely at the limit of the technological feasibility which is described by the curve of the parameter value function.

The third step is used to calculate the dimensionless innovation figure φ. It is formed by computing the arithmetic mean of all similarity indicators ξ_i. Depending on the importance of the single indicators, a weighted mean can be helpful to achieve results of higher quality. A decision can be made during the qualification of the model in the first method. One reason for preferring the weighted mean over the arithmetic mean can be, if the chosen technical parameters describe equal technical hurdles. In this case, it is suggested to form groups of similarity indicators and weaken their impact by appropriate weighting factors in a way that a balanced image of the actual product is generated.

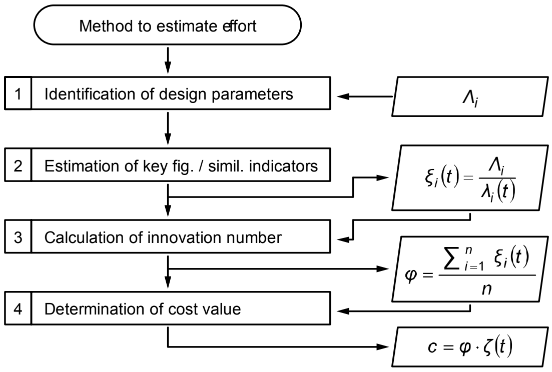

Fig. 4. Steps of the method for estimating the effort

The determination of the specific cost value *c* can be considered the last step. This is achieved by multiplying the dimensionless innovation figure φ with the cost function of the model ζ. Depending on whether a single product (typically for low volume products) or a complete product programme (respectively for high volume products) has been taken into account for the establishment of the cost function in the cost plot, the estimation of the effort needed for the intended product development project can be specified.

3.4. Integration in a Product Lifecycle Engineering platform

Typically, the methodology is not limited to an exclusive estimation of the product development effort. In fact, most products for which the forecast has been conducted will eventually be manufactured after having passed through the design phase. The actually accumulated costs can be precisely measured and compared with the originally estimated costs. On the one hand, this feedback – considered as validation of the methodology – is fundamentally required to check whether the qualified model (as described in section 3.2) is applicable for the desired purpose of estimating the development costs. Amongst others, this is depending on the meaningful choice of the considered parameters. On the other hand, the feedback is necessary to integrate new data points into the parameter value and cost plots to further refine the data base. As more interpolation points are integrated into the model, the prospective estimations will be more precise. The validation and feedback loops are displayed in Fig. 1.

In case the methodology is to be permanently integrated into the product design process of a company, it is especially required to incorporate latest data as otherwise the model would soon be outdated for the estimation of current project costs.

The methodology presented here was developed as part of a large scale lifecycle assessment approach aiming at covering the complete aircraft lifecycle, as laid out in [13]. It has been integrated in a lifecycle engineering platform for assessing the preliminary design and its effects on manufacturing, operating and ground handling as well as recycling aspects. The integration of the different modules offers the advantage of conducting sensitivity analyses to obtain knowledge about the influences changes to specific parameters have on the whole lifecycle of the product. Moreover, the insights gained can directly be fed back into the model with the intention to further improve the quality of the available lifecycle date.

4. Exemplary application in civil aircraft industry

The methodology presented in section 3 has been exemplarily applied for the cost estimation of the design process of civil aircraft featuring more than 100 passenger seats. In this course, both model qualification and the actual estimation method have been run through. The second method has been supported by an accompanying software prototype implemented to seamlessly integrate with the lifecycle assessment platform mentioned in section 3.4.

In preliminary aircraft design, it is common practice to define the main concept requirements as so called Top Level Aircraft Requirements (TLAR) [14]. Typically, they are defined before the actual engineering design and development lots are carried out. In addition, for aircraft already present on the market, these TLAR can be extracted from manufacturer brochures. Hence, the availability of suitable data can be secured. It is obvious that the required technical parameters used for the model presented here can be taken from the set of TLAR. For the application, a suitable set of technical parameters had to be extracted from the TLAR. Thereafter, the general feasibility for the qualification of the model of each parameter had to be tested. Fig. 5 displays the chosen parameters.

Parameter	Description	TLAR
λ_1, Λ_1 and ξ_1	Max. Takeoff Weight	*MTOW*
λ_2, Λ_2 and ξ_2	Max. Landing Weight / Landing Field Length	$\frac{MLW}{LFL}$
λ_3, Λ_3 and ξ_3	Number of seats · Range	$Seats \cdot R$
λ_4, Λ_4 and ξ_4	Number of seats / Operating Weight Empty	$\frac{Seats}{OWE}$
λ_5, Λ_5 and ξ_5	Max. Payload · Range / Sea Level Static Thrust	$\frac{Max.\ Payload \cdot R}{SLST}$

(Number of parameters $n = 5$)

Fig. 5. Parameters used in example implementation

As expected, the maximum take-off weight played a key role and had huge influence on the development costs. However, implementing solely this parameter turned out to only deliver unsatisfying results. Although the weight is one of the moving factors in the aerospace industry other trends (as for instance the continuously increasing number of maximum passenger seats) influence the development costs in a way that cannot be neglected. It becomes clear, that more parameters are required to describe the technological feasibility expressed by the parameter value functions.

Some technical parameters turned out to have no significant or no unambiguous influence on the development effort. For example, the emitted noise has noteworthy impact on the design of the geometry of the aircraft as well as on the design of the engines. However, no distinct smoothing function could be derived from the according parameter value plot. Concluding, five parameters (both directly used single values and combinations of several parameters) were identified, which had significant influence on development costs. They have been implemented in a software prototype using Excel worksheets, as displayed in Fig. 6. For communication with the platform addressed in section 3.4, a custom designed xml interface was developed to connect Excel and the existing xml structure of the platform [15].

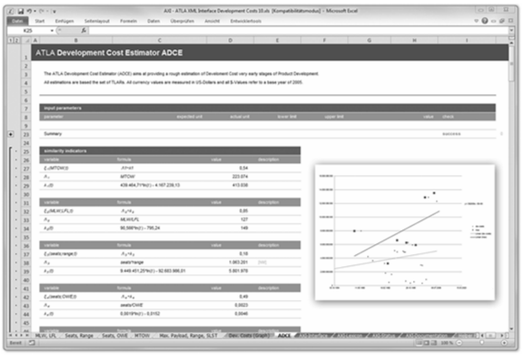

Fig. 6. Prototypical implementation with detail view of parameter value plot

An extensive verification with actual aircraft development projects (comprised of projects that have been included in the model qualification as well as projects that have been intentionally left out for validation purposes) proved that the average deviation of the estimated costs compared with the actual costs was not greater than 21.9 %. The hypotheses postulated in the beginning could thus be considered as valid. The methodology itself is able to predict development effort measured in costs with satisfactory accuracy only relying on lifecycle data from previous developments.

5. Summary and outlook

The paper demonstrated how development effort and accordingly the development costs of products can be estimated based on few requirements, the so called technical parameters. This estimation takes place before the actual development has begun. The proposed methodology is applicable independently from the product type or industrial sector as a consequence of its two-part structure. Data used originates from lifecycle assessment for similar products and can be used to extrapolate the lifecycle impact of the product under development. Exemplarily, an application for civil aircraft design has been presented. The tool implemented for the described method has been integrated into a lifecycle engineering platform.

The methodology addressed in this paper is subject to current research at RWTH Aachen University. Future investigations will concentrate on generalising the applicability of the method by searching for sets of technical parameters that are valid for specific industrial sectors. Further validation of the methodology with different other application examples is pursued.

Acknowledgements

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References

[1] Wolfram M. Feature-basiertes Konstruieren und Kalkulieren. München: Hanser; 1994.
[2] Horváth P, Gleich R, Scholl K. Vergleichende Betrachtung der bekanntesten Kalkulationsmethoden für das kostengünstige Konstr. In: Männel W, ed. Frühzeitiges Kostenmanagement: Kalkulationsmethoden und DV-Unterst. Wiesbaden: Gabler; 1997. p. 111–31.
[3] Ehrlenspiel K, Kiewert A, Lindemann U. Kostengünstig Entwickeln und Konstruieren: Kostenmanagement bei der integr. Produktentwicklung. 6th Ed. Berlin: Springer; 2007.
[4] Feldhusen J, Koy M. Methode zur Produktivitätsmessung für Entwicklung und Konstruktion. Konstruktion 2002; (9):49–54.
[5] Hichert R. Praktische Ansätze zur Termin-, Kapazitäts- und Kostenplanung in Entwicklung und Konstruktion. In: Moll HH, ed. RKW-Handbuch Forschung, Entwicklung. Berlin: Schmidt; 1976
[6] Boehm B. Software Engineering Economics. Englewood Cliffs: Prentice-Hall; 1981.
[7] Boehm B, Clark B, Horowitz E, Westland C, Madachy R, Selby R. Cost Models for Future Software Life Cycle Processes: COCOMO 2.0. Annals of Software Engineering 1995; 1(1) pp. 57–94.
[8] Feldhusen J, Pollmanns J, Heller JE. Prognose des Entwicklungsaufwands: Adaption des COCOMO Modells auf die Produktentwicklung. In: Brökel K, Feldhusen J et al. eds. 8. Gem. Kolloquium Konstruktionstechnik 2010. Barleben: docupoint; 2010 .
[9] Hauschild J, Schlaak TM. Zur Messung des Innovationsgrades neuartiger Produkte. Zeitschrift für Betriebswirtschaft 2001; 71.
[10] Raymer DP. Aircraft Design: A Conceptual Approach. Washington, D.C: American Institute of Aeronautics and Astronautics; 1989.
[11] Roskam J. Airplane Design: Airplane Cost Estimation. Ottawa: Roskam Aviation and Engineering Corporation; 1990. (Airplane Design; Vol 8).
[12] Duverlie P, Castelain JM. Cost Estimation During Design Step: Parametric Method versus Case Based Reasoning Method. Int J Adv Manuf Technol 1999; (15) pp. 895–906.
[13] Franz K, Hörnschemeyer R, et al. A methodical approach to assess the aircraft life cycle. In: Air Transport and Operations Symp. Delft; 2011.
[14] Franz K, Hörnschemeyer R et al. Life Cycle Engineering in Preliminary Aircraft Design. In: Dornfeld DA, Linke BS, eds. Leveraging Technology for a Sustainable World: Proc. of the 19th CIRP Conference on Life Cycle Engineering. Heidelberg: Springer; 2012. pp. 473–478 .
[15] Risse K, Anton E, Lammering T, Franz K et al. An Integrated Environment for Preliminary Aircraft Design and Optimization. In: 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 2012.